4th European HICUM Workshop

HICUM temperature scaling laws and parameter extraction

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1. Introduction

Model parameters for modeling the temperature dependence can in principle be obtained by repeating the extraction methods at different temperature.

But, HICUM model is described by 82 electrical parameters. In the temperature range, [-40^{o}C;180^{o}C], with n different temperatures, this method requires the extraction of n.82 parameters for only one transistor!
The extraction effort can be significantly reduced thanks to the study of physical quantities, like intrinsic carrier or mobility, dependence with temperature.
This study makes it possible to establish parameter temperature dependence, thanks to parameter value at T_{NOM}, and the extraction of temperature parameters: $P(T) = P(T_{NOM}) \cdot f(T, T_{NOM})$.
The question is: how extract HICUM temperature parameters?
Two methods are possible:

- Repeating the extraction methods at different temperature, and then extract HICUM temperature parameters from P(T) curves.

- Extracting HICUM temperature parameters from temperature measurements of electrical data, which are well impacted by these parameters.

To compare these approaches, measurements at different temperature were made, and model parameters were extracted at each temperature. Then the comparison with parameter temperature variation predicted by HICUM model was done.

2. HICUM model equations: temperature dependence

2.1. HICUM temperature dependence parameters

N°	Name	Description	Default	Unit
1	V_{GB}	Bandgap-voltage at 0K	1.17	V
2	A_{LB}	Relative temperature coefficient of forward current gain	5.10^{-3}	1/K
3	A_{LT0}	First-order relative temperature coefficient of T_{F0}	0	1/K
4	K_{T0}	Second-order relative temperature coefficient of T_{F0}	0	$1/K^2$
5	Z_{ETACI}	Temperature exponent for R_{CI0}	0	-
6	A_{LVS}	Relative temperature coefficient of saturation drift velocity	0	1/K
7	A_{LCES}	Relative temperature coefficient of V_{CES}	0	1/K
8	Z_{ETARBI}	Temperature exponent of internal base resistance	0	-
9	Z_{ETARBX}	Temperature exponent of external base resistance	0	-
10	Z_{ETARCX}	Temperature exponent of external collector resistance	0	-
11	Z_{ETARE}	Temperature exponent of external emitter resistance	0	-
12	A_{LFAV}	Relative temperature coefficient for F_{AVL}	0	1/K
13	A_{LQAV}	Relative temperature coefficient for Q_{AVL}	0	1/K

2.2. HICUM model equations

Name	Description	Unit
T	Temperature at which the device is simulated	K
T_{NOM}	Temperature at which model parameters have been extracted	K
ΔT	$\Delta T = T - T_{NOM}$	K
T_R	$T_R = \frac{T}{T_{NOM}}$	-

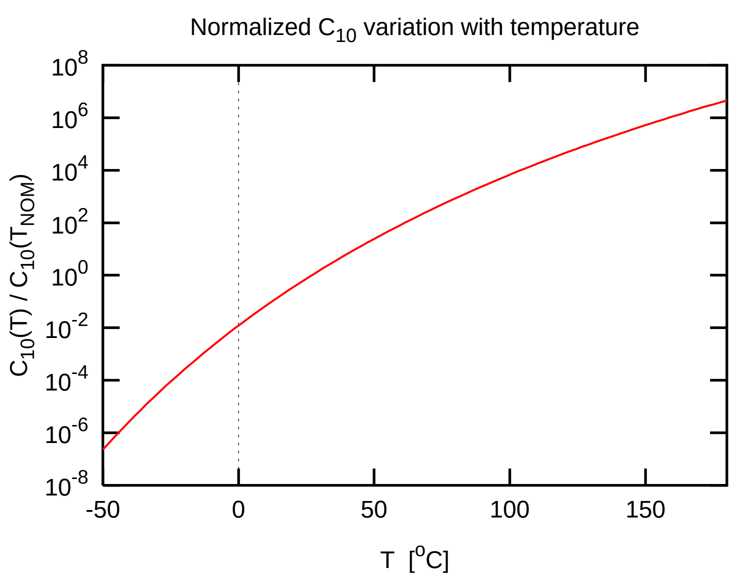
→ Transfer current

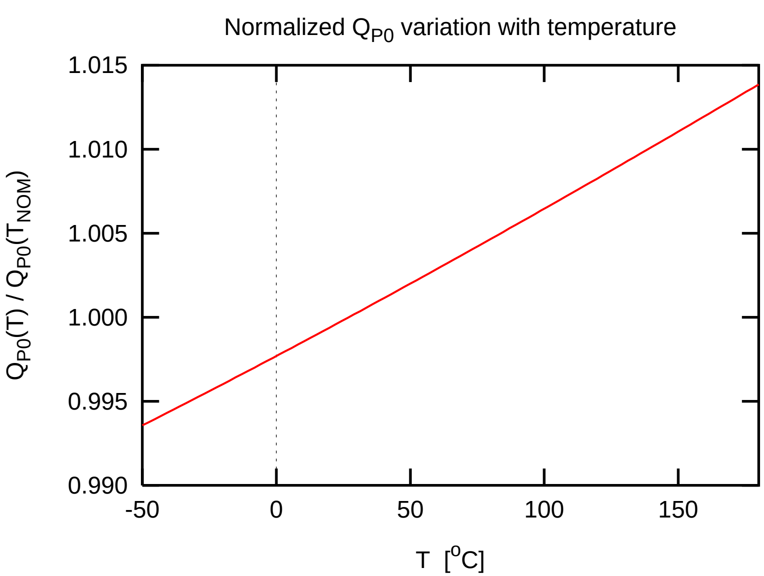
The transfer current is strongly temperature dependent via the intrinsic carrier density.This leads to:

$$\boxed{c_{10}(T) = c_{10}(T_{NOM}) \cdot {T_R}^3 \cdot \exp\left(\frac{V_{GB}}{V_T} \cdot (T_R - 1)\right)}$$

The zero-bias hole charge Q_{p0} is temperature dependent via the influence of base width change with temperature, that is mainly caused by the change in depletion width of the BE junction:

$$\boxed{Q_{p0}(T) = Q_{p0}(T_{NOM}) \cdot \left[1 + \frac{z_{Ei}}{2} \cdot \left\{1 - \frac{V_{DEi}(T)}{V_{DEi}(T_{NOM})}\right\}\right]}$$





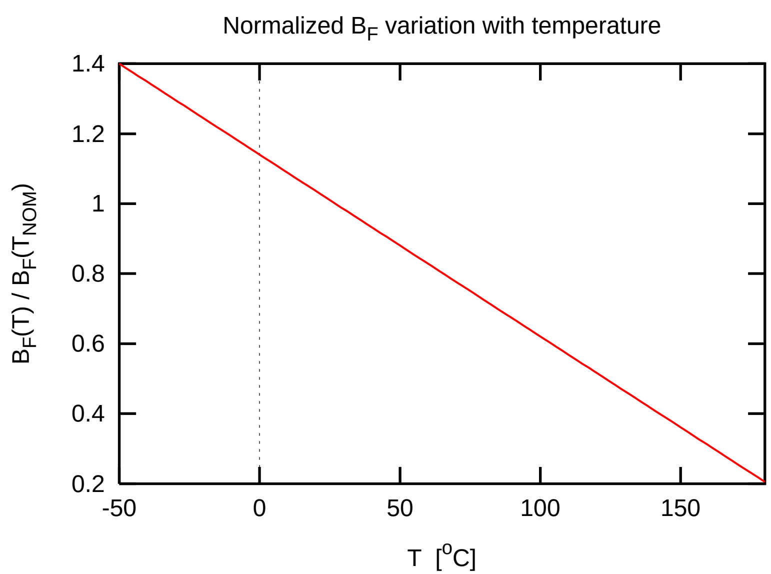
Current gain and base current

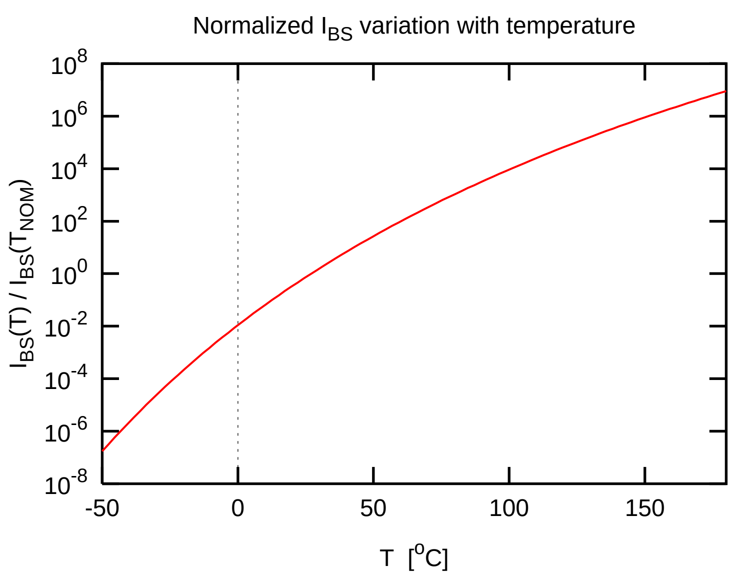
In HICUM, the temperature dependence of the forward current gain is given by:

$$B_F(T) = B_F(T_{NOM}) \cdot \{1 + A_{LB} \cdot \Delta T\}$$

Thus the temperature dependence of the saturation base current can be written:

$$\boxed{I_{BS}(T) = I_{BS}(T_{NOM}) \cdot T_R^{\;3} \cdot \exp\left\{\frac{V_{GB}}{V_{T_{NOM}}} \cdot \left(1 - \frac{1}{T_R}\right) - A_{LB} \cdot \Delta T\right\}}$$

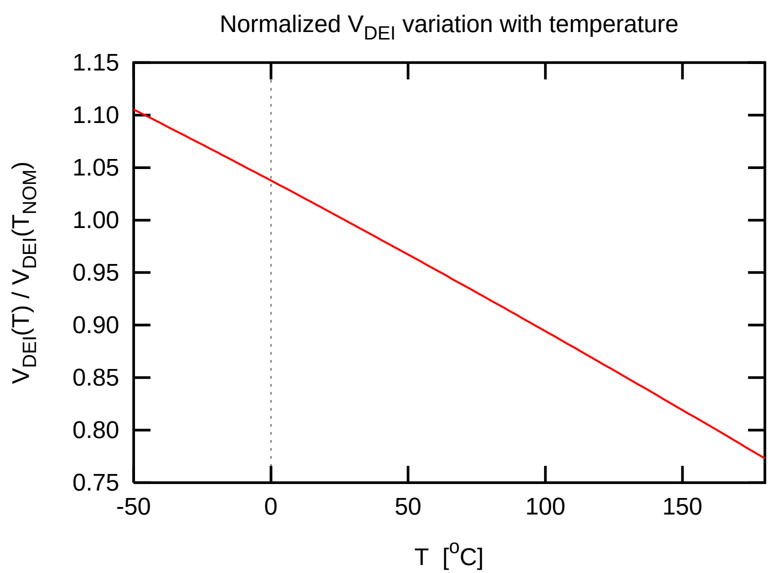


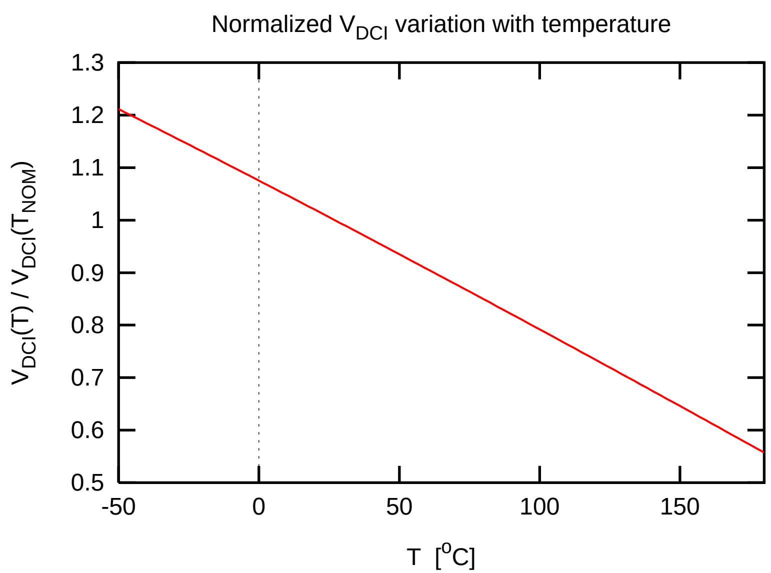


➔ Depletion charges and capacitances

The key parameter for the temperature dependence of the depletion charges and capacitances is the diffusion (or built-in) voltage:

$$\boxed{V_D(T) = V_D(T_{NOM}) \cdot T_R + V_{GB} \cdot (T_R - 1) - 3 \cdot V_T \cdot \ln(T_R)}$$



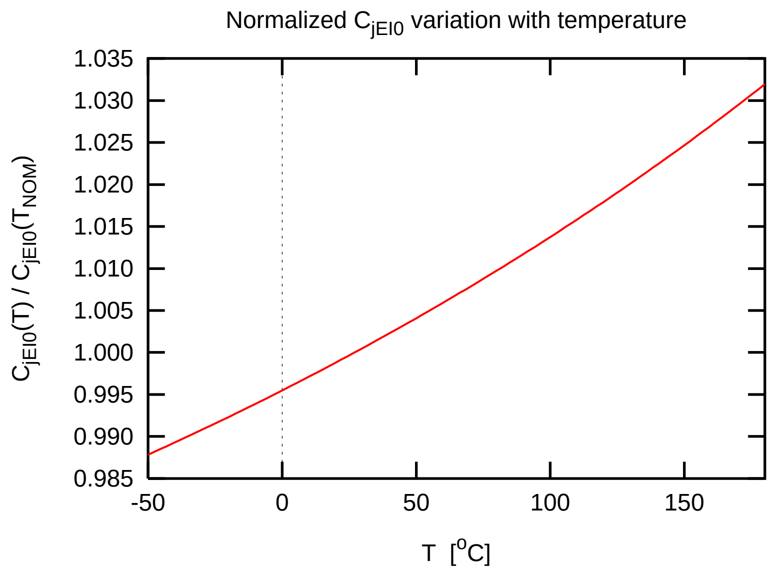


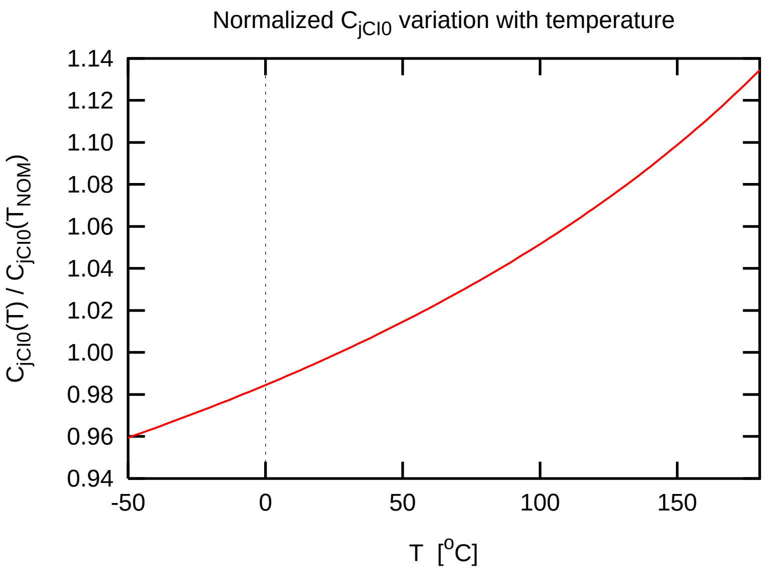
The parameter A_{LJ} determining the maximum value of the depletion capacitance at forward bias is empirically modified as follows:

$$\boxed{A_{LJ}(T) = A_{LJ}(T_{NOM}) \cdot \frac{V_D(T)}{V_D(T_{NOM})}}$$

The zero-bias junction capacitance temperature dependence can be directly calculated from that of V_D:

$$\boxed{C_{j0}(T) = C_{j0}(T_{NOM}) \cdot \left(\frac{V_D(T_{NOM})}{V_D(T)}\right)^Z}$$

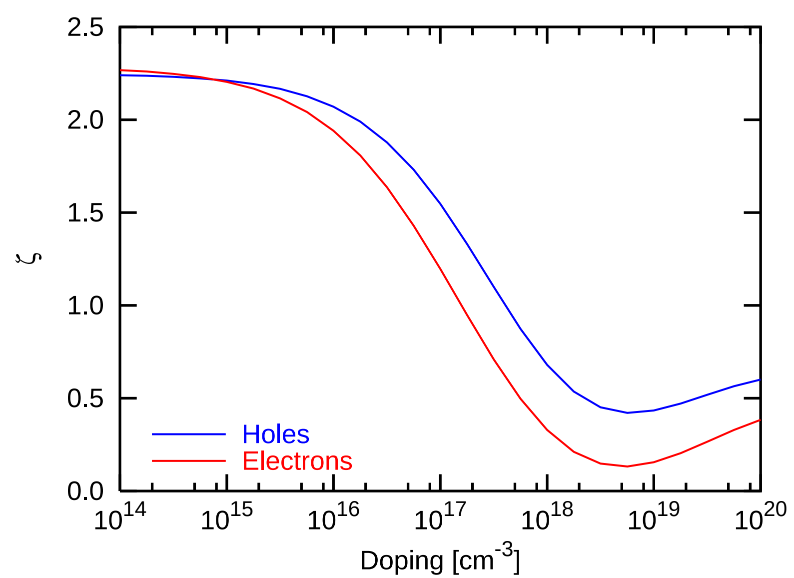




➔ Temperature coefficients of sheet resistances

Temperature dependence of sheet resistances can be determined according to the temperature dependence of the mobility assuming: $\mu(T) = \mu(T_{NOM}) \cdot T_R^{-\zeta}$ leading to: $\boxed{R(T) = R(T_{NOM}) \cdot T_R^{\zeta}}$

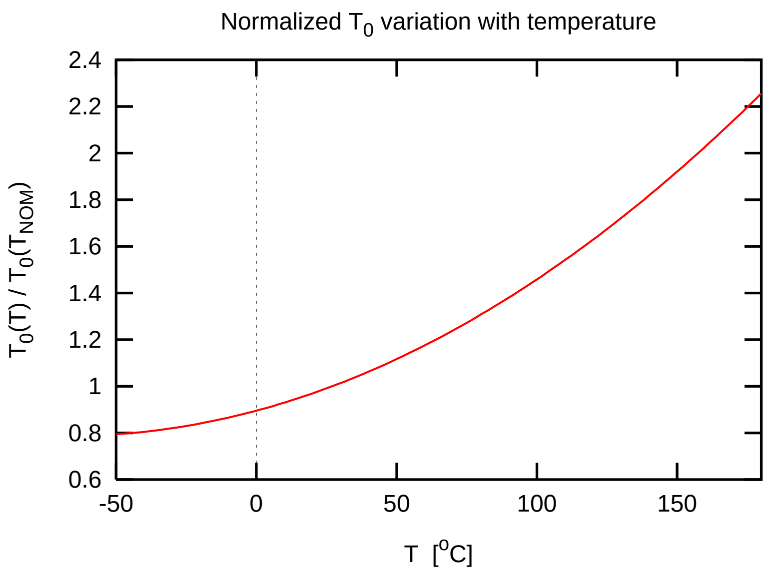
The mobility exponent ζ can be expressed by an empirical function of the average doping concentration N of the concerned region: $\zeta(N) = \dfrac{a + c \cdot x + e \cdot x^2 + g \cdot x^3}{1 + b \cdot x + d \cdot x^2 + f \cdot x^3}$ where x is the decimal logarithm of the doping level $x = \log N$ (1)



Transit time and minority charge

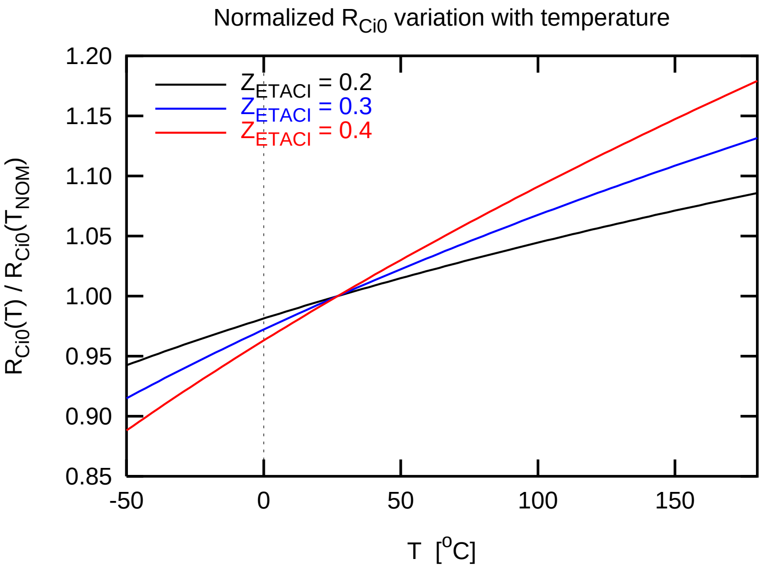
The low-current portion of the transit time as a function of temperature is mainly determined by the quadratic temperature dependence of the parameter T_0:

$$\boxed{T_0(T) = T_0(T_{NOM}) \cdot [1 + A_{LT0} \cdot \Delta T + K_{T0} \cdot \Delta T^2]}$$



The critical current density I_{CK} depends on temperature via physical parameters like mobility of the epitaxial collector and saturation velocity. The internal collector resistance contains the low-field electron mobility and reads:

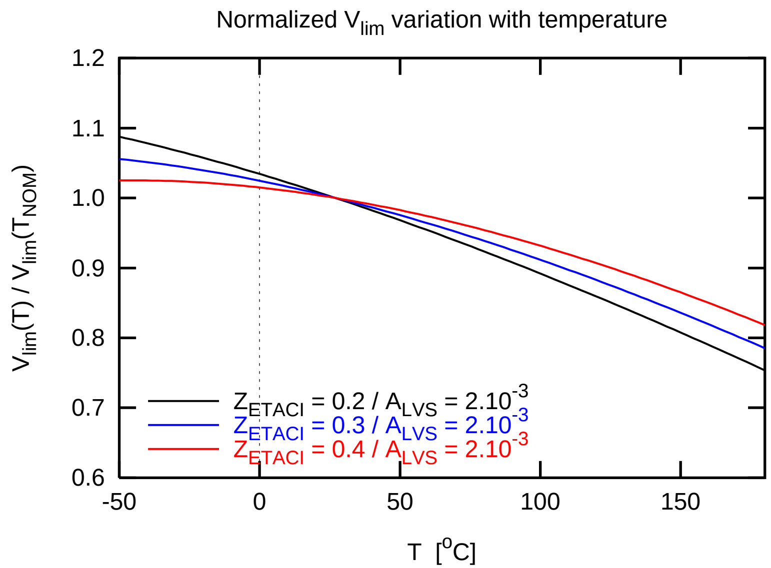
$$\boxed{R_{Ci0}(T) = R_{Ci0}(T_{NOM}) \cdot T_R^{\,Z_{ETACI}}}$$

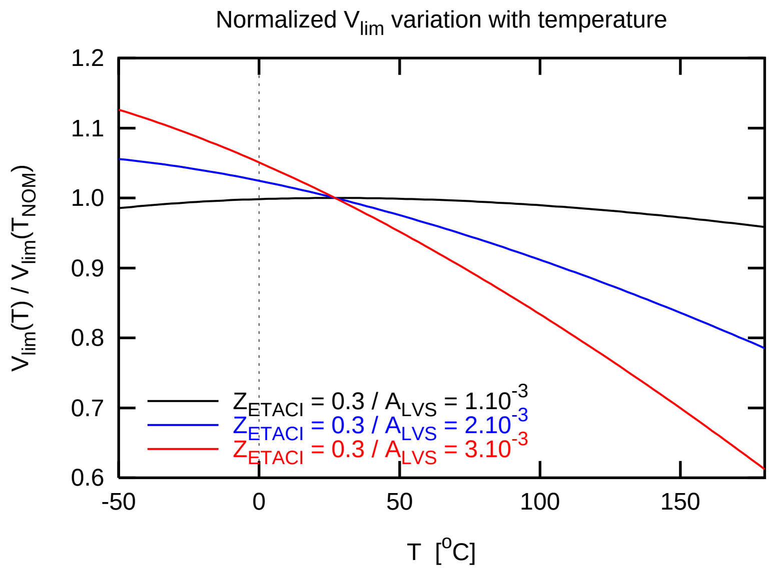


The model parameter Z_{ETACI} is a function of the collector doping concentration.

The voltage V_{lim} contains both mobility and saturation velocity, resulting in:

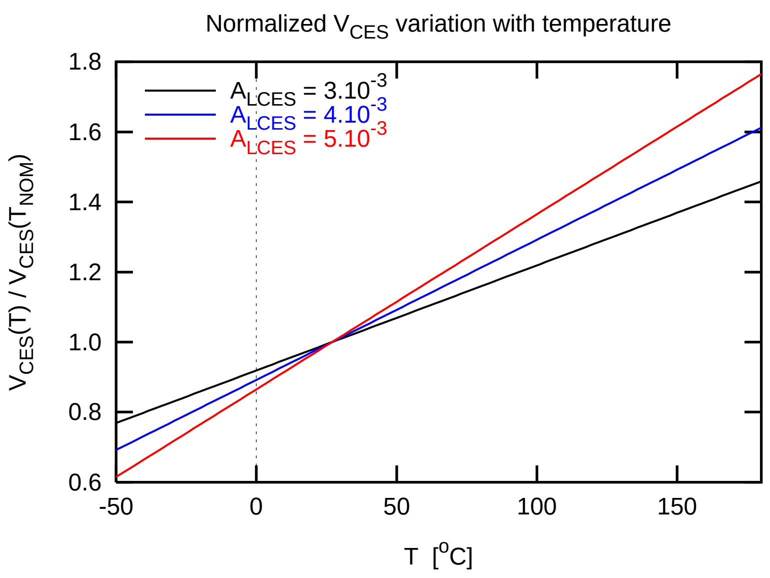
$$\boxed{V_{lim}(T) = V_{lim}(T_{NOM}) \cdot (1 - A_{LVS} \cdot \Delta T) \cdot T_R^{ZETACI}}$$





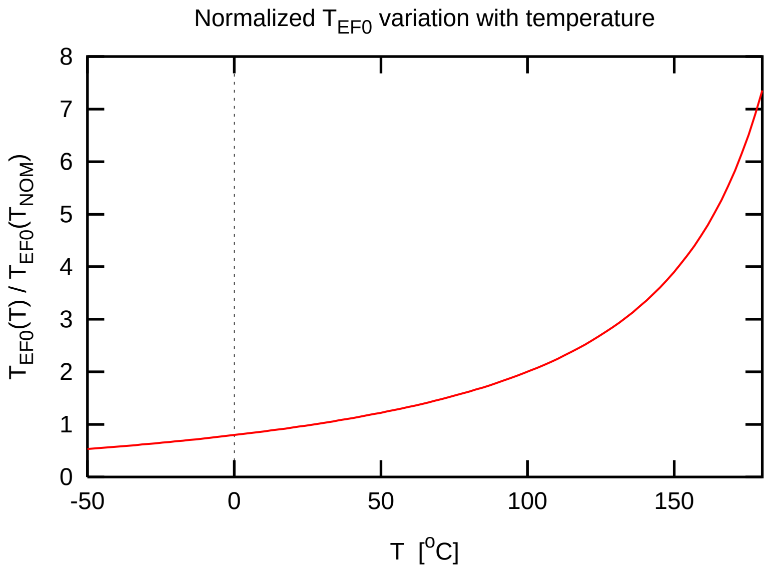
The CE saturation voltage is modelled as a linear function of temperature:

$$\boxed{V_{CES}(T) = V_{CES}(T_{NOM}) \cdot (1 + A_{LCES} \cdot \Delta T)}$$



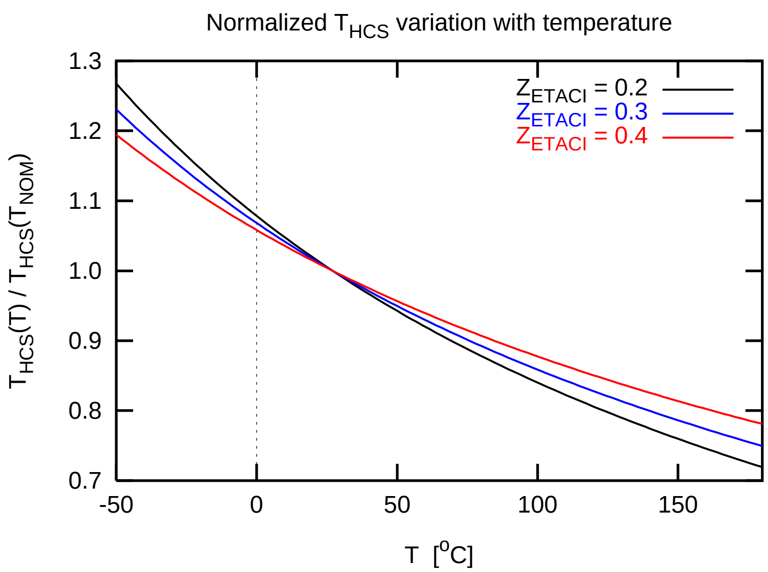
The emitter time constant T_{EF0} depends on temperature via mainly the hole diffusivity in the neutral emitter and the current gain. Assuming a large emitter concentration with a negligible temperature dependence of the mobility, the following expression can be obtained:

$$\boxed{T_{EF0}(T) = T_{EF0}(T_{NOM}) \cdot \frac{T_R}{1 + A_{LB} \cdot \Delta T}}$$



The temperature dependence of the parameter T_{HCS} can be expressed as:

$$\boxed{T_{HCS}(T) = T_{HCS}(T_{NOM}) \cdot T_R^{(Z_{ETACI} - 1)}}$$

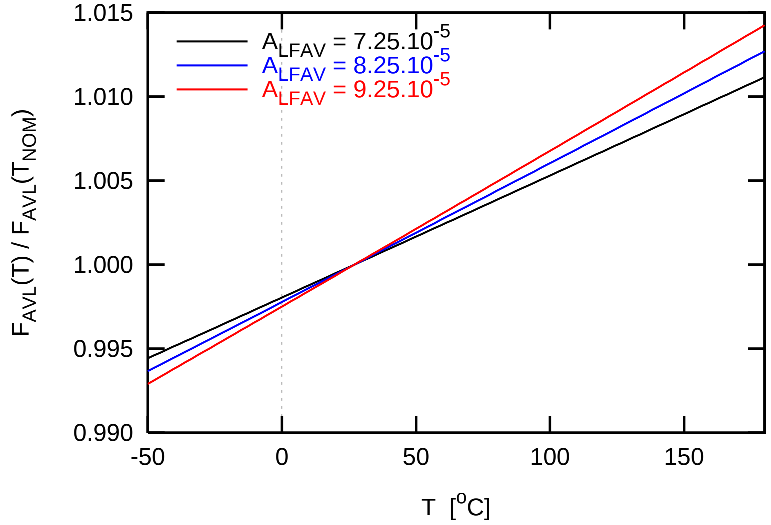


Avalanche current

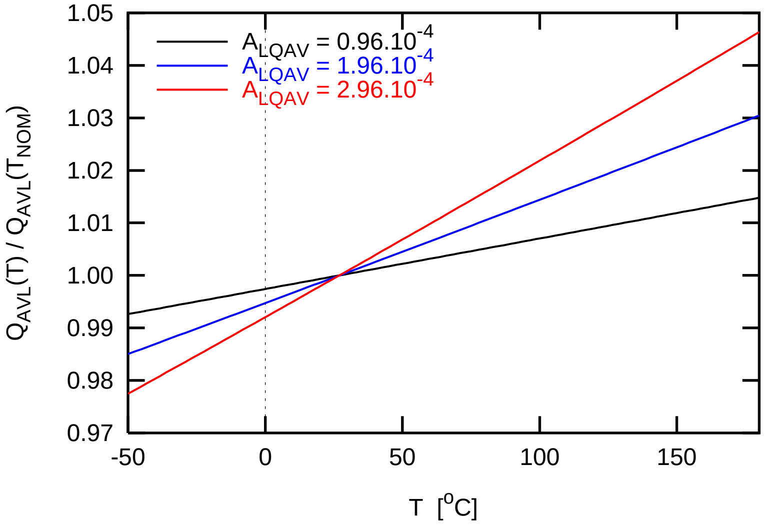
$$F_{AVL}(T) = F_{AVL}(T_{NOM}) \cdot \exp(A_{LFAV} \cdot \Delta T)$$

$$Q_{AVL}(T) = Q_{AVL}(T_{NOM}) \cdot \exp(A_{LQAV} \cdot \Delta T)$$

Normalized F_{AVL} variation with temperature



Normalized Q_{AVL} variation with temperature



2.3. Summary

- Presentation of HICUM temperature dependence model equation and HICUM temperature dependence parameters
- Model prediction

Parameter	Variation with temperature	$\frac{dParameter}{dT}$
C_{10}	2.10^{4} K^{-1}	+
Q_{P0}	8.10^{-5} K^{-1}	+
I_{BS}	4.10^{4} K^{-1}	+
V_D	0.003 K^{-1}	-
A_{LJ}	0.003 K^{-1}	-
C_{j0}	8.10^{-4} K^{-1}	+
T_0	0.006 K^{-1}	+
R_{Ci0}	0.001 K^{-1}	+
V_{lim}	0.002 K^{-1}	-
V_{CES}	0.005 K^{-1}	+
T_{EF0}	0.03 K^{-1}	+
T_{HCS}	0.002 K^{-1}	-
F_{AVL}	10^{-4} K^{-1}	+
Q_{AVL}	3.10^{-4} K^{-1}	+

$$\boxed{\frac{P_{NORM}(T_{max}) - P_{NORM}(T_{min})}{T_{max} - T_{min}}}$$

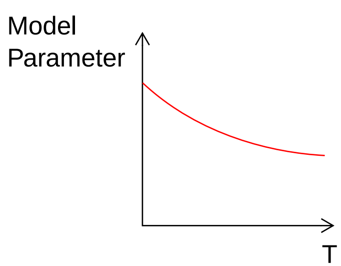
$T_{max} = 180^{o}C$

$T_{min} = -50^{o}C$

3. Comparison between direct extraction and HICUM temperature laws

MEASUREMENT @ $T_{min}<T<T_{max}$

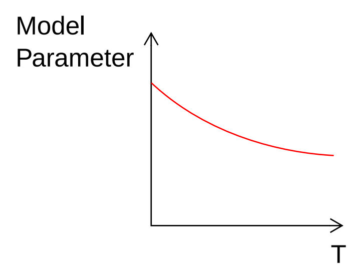
n model cards @ $T_{min}<T<T_{max}$



Model parameter variation with temperature without temperature parameter extraction

MEASUREMENT @ $T=T_{NOM}$

1 model card @ $T=T_{NOM}$



Model parameters variation with temperature deduced from temperature parameter extraction

$\boxed{P(T)=P(T_{NOM}).f(T,T_{NOM})}$

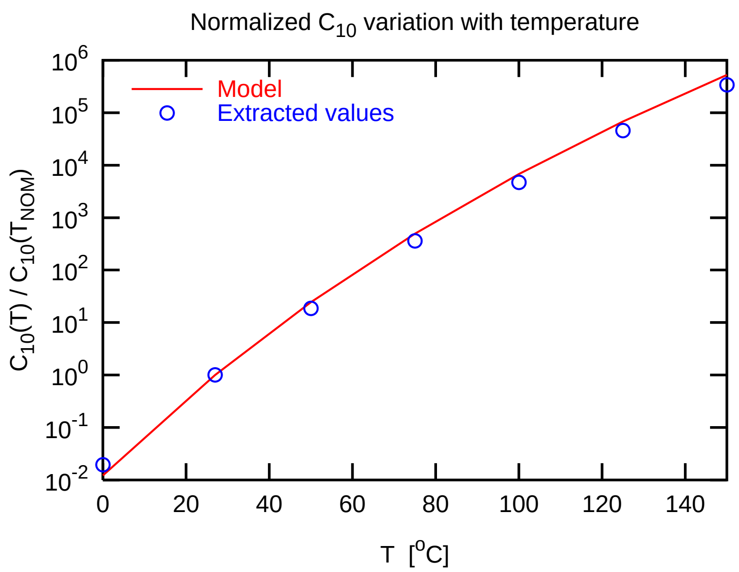
COMPARISON

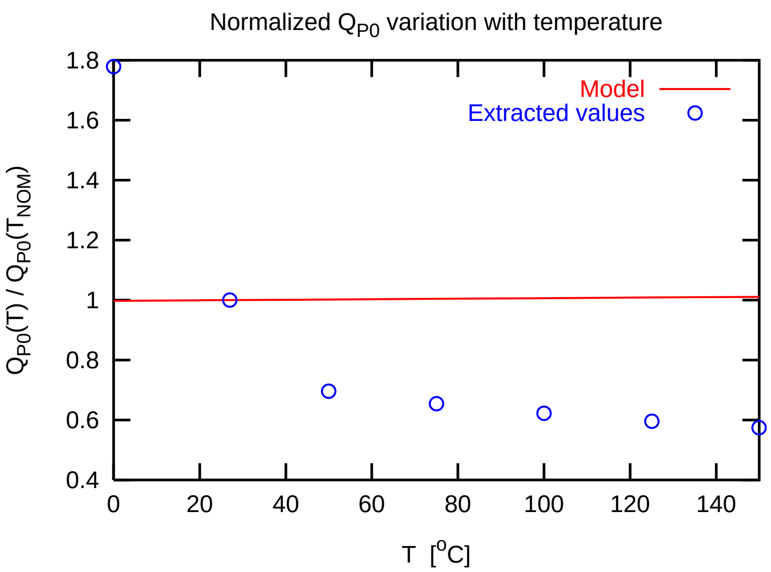
The measurements were made on a SiGe:C BiCMOS technology with a f_T peak at 55 GHz.

➔ Transfer current

$$c_{10}(T) = c_{10}(T_{NOM}) \cdot T_R{}^3 \cdot \exp\left(\frac{V_{GB}}{V_T} \cdot (T_R - 1)\right)$$

$$Q_{p0}(T) = Q_{p0}(T_{NOM}) \cdot \left[1 + \frac{z_{Ei}}{2} \cdot \left\{1 - \frac{V_{DEi}(T)}{V_{DEi}(T_{NOM})}\right\}\right]$$



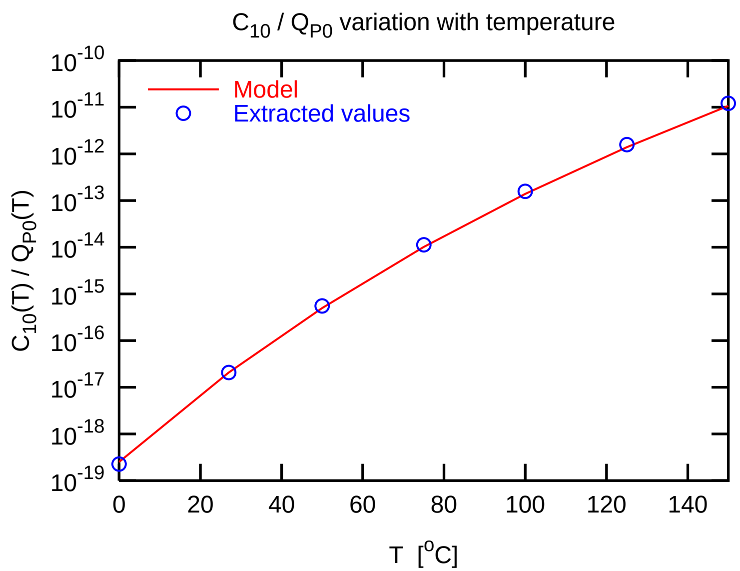


MAX: 60% gap from model

MAX: 70% gap from model

➜ Saturation current

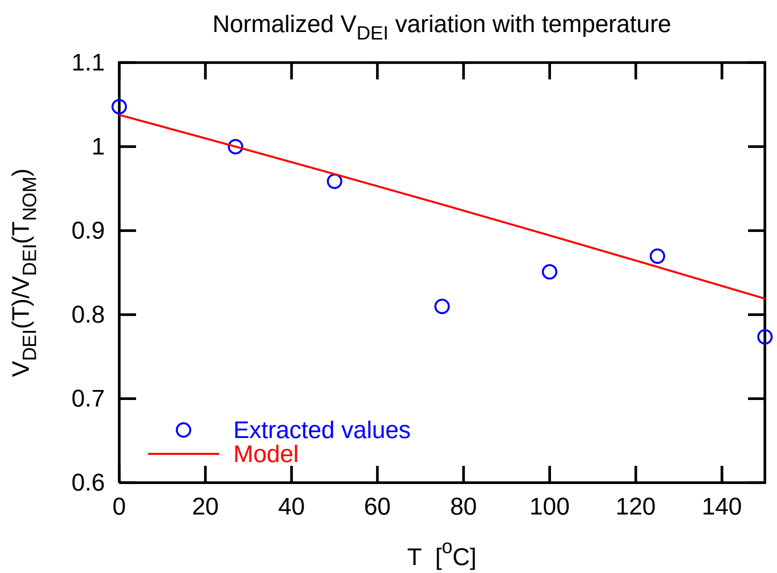
$$\boxed{I_S(T) = I_S(T_{NOM}) \cdot T_R^{\ 3} \cdot \exp\left\{\frac{V_{GB}}{V_{T_{NOM}}} \cdot \left(1 - \frac{1}{T_R}\right)\right\} = \frac{C_{10}(T)}{Q_{P0}(T)}}$$

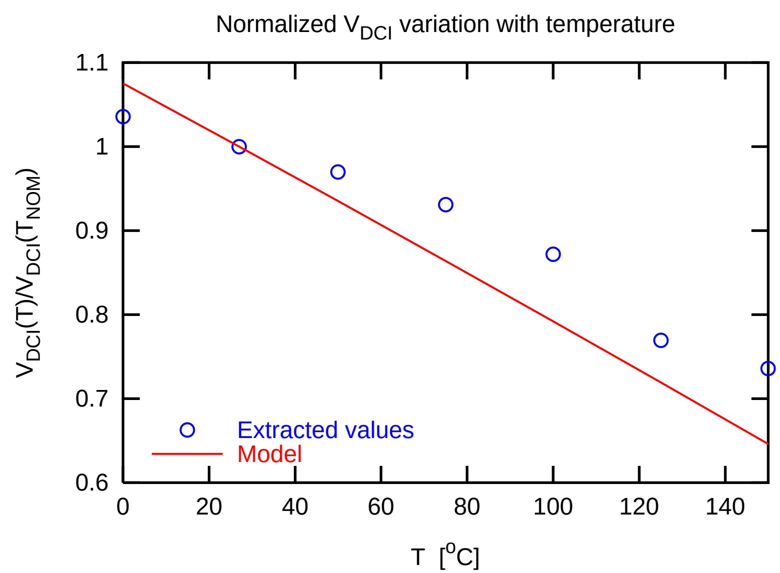


MAX: 15% gap from model

→ Depletion charges and capacitances

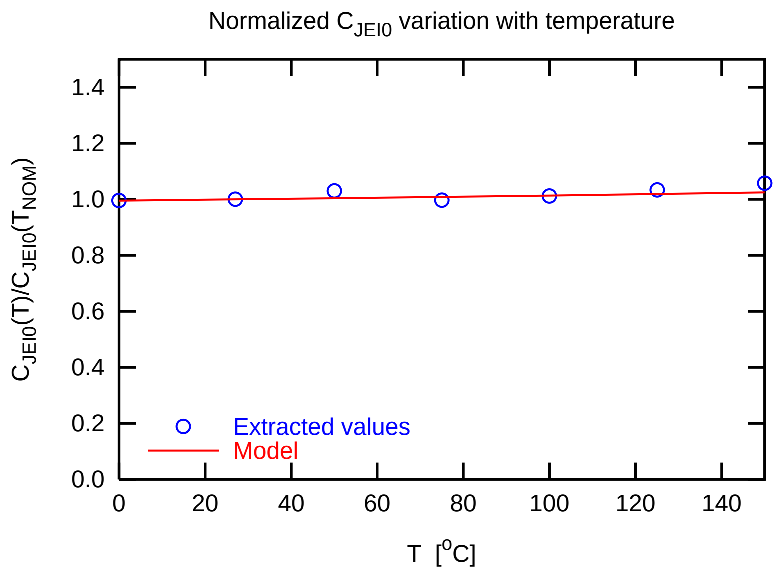
$$\boxed{V_D(T) = V_D(T_{NOM}) \cdot T_R + V_{GB} \cdot (T_R - 1) - 3 \cdot V_T \cdot \ln(T_R)}$$

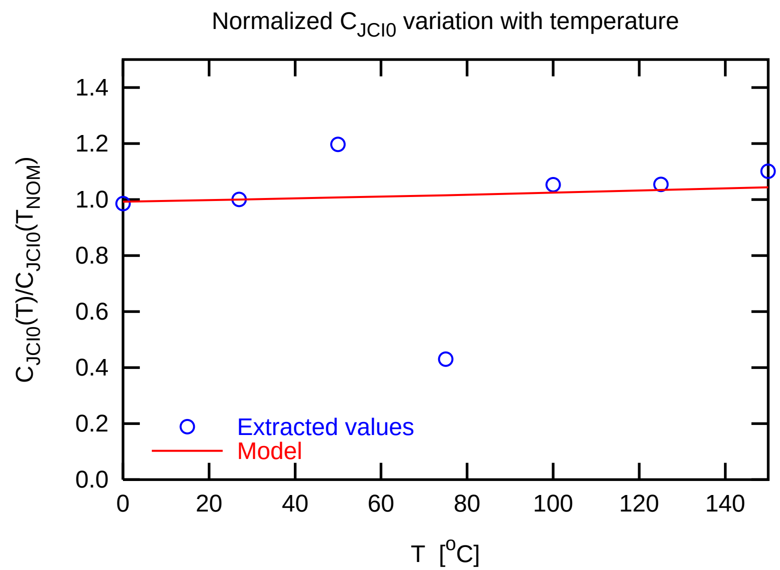




MAX: 10% gap from model

$$C_{j0}(T) = C_{j0}(T_{NOM}) \cdot \left(\frac{V_D(T_{NOM})}{V_D(T)}\right)^Z$$





MAX: 3.5% gap from model

MAX: 60% gap from model

4. Temperature parameter extraction methods

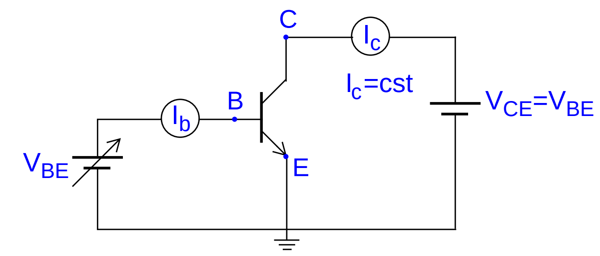
4.1. Principle

Model parameters for modeling the temperature dependence can in principle be obtained by repeating the extraction me thods at different temperature.
As we observed in previous part, this method adds error to temperature parameter extraction error, due to the extraction of electrical parameters at different temperature. This is particularly true for parameters which have a slow variation with temperature, as the built-in voltage or depletion capacitance.

Another approach is temperature parameter extraction from temperature measurements of electrical data, which are well impacted by the model parameters. This allows to minimize error due to extraction methods.

→ PROMOTE DIRECT EXTRACTIONS FROM TEMPERATURE MEASUREMENTS

4.2. Bandgap voltage



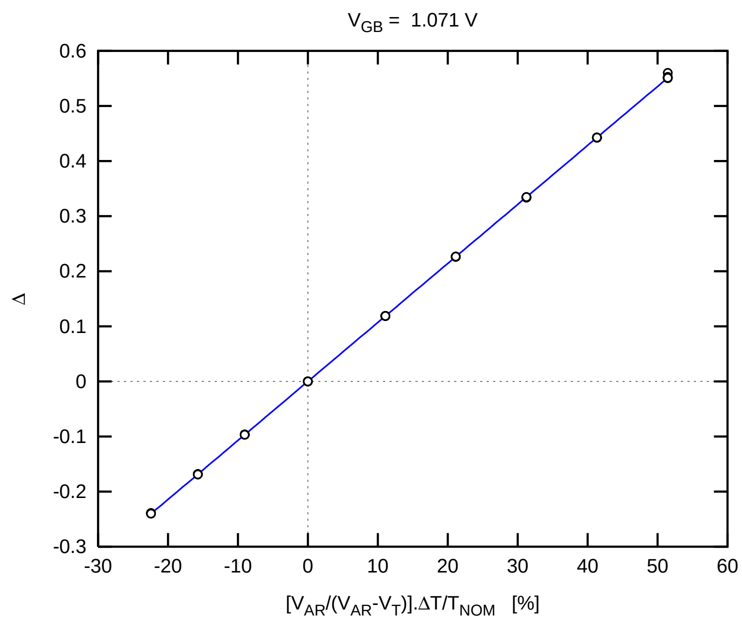
Measurement data: $V_{BE}(T)$ data at V_{BC}=0 at different constant I_C

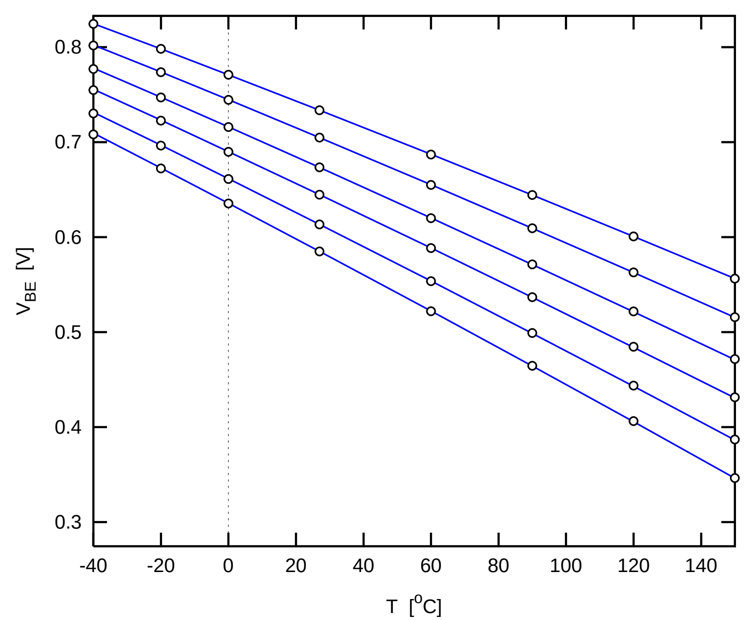
Required model parameters: none

Procedure: Linear regression on the curve:

$$\Delta = V_{BE}(T_{NOM}) \cdot T_R \cdot \frac{V_{AR} - V_{T_{NOM}}}{V_{AR} - V_T} - V_{BE}(T) - 3 \cdot \frac{V_{AR} \cdot V_T}{V_{AR} - V_T} \cdot \ln T_R = \frac{V_{AR}}{V_{AR} - V_T} \cdot V_{GB} \cdot \frac{\Delta T}{T_{NOM}}$$

Related HICUM parameter: V_{GB}





→ Bandgap voltage temperature dependence parameter

$$I_C(T) = \frac{I_S(T)}{1 + h_{jEi}\cdot\frac{Q_{jEi}(T)}{Q_{p_0}(T)}}\exp\left(\frac{V_{BE}(T)}{V_T}\right) \text{ with } I_S(T) = I_S(T_0)\cdot T_R^{\ 3}\cdot\exp\left\{\frac{V_{GB}}{V_{T_{NOM}}}\cdot\left(1-\frac{1}{T_R}\right)\right\}$$

But, instead of considering the variation of $1 + h_{jEi}\cdot\frac{Q_{jEi}(T)}{Q_{p_0}(T)}$, the expression of the collector current is considered to be:

$$I_C(T) = \frac{I_S(T)}{1 + \frac{V_{BE}(T)}{V_{AR}}}\exp\left(\frac{V_{BE}(T)}{V_T}\right)$$

Thus, assuming that $1 \gg \frac{V_{BE}(T)}{V_{AR}}$, $\frac{1}{1+\frac{V_{BE}(T)}{V_{AR}}} \approx \exp\left(-\frac{V_{BE}(T)}{V_{AR}}\right)$, which leads to the expression of I_C:

$$I_C(T) = I_S(T)\cdot\exp\left(\frac{V_{BE}(T)}{V_T} - \frac{V_{BE}(T)}{V_{AR}}\right).$$

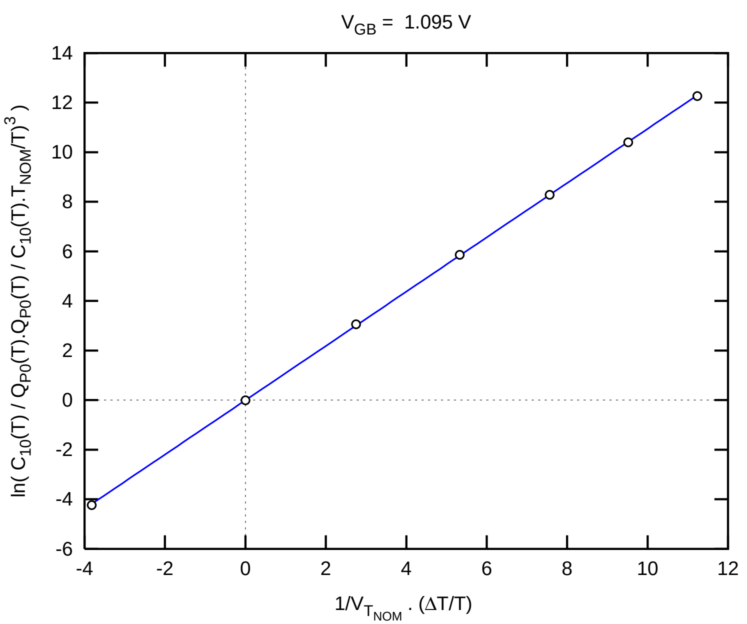
Finally: $I_C(T) = I_C(T_{NOM})\cdot T_R^{\ 3}\cdot\exp\left\{\frac{V_{GB}}{V_{T_{NOM}}}\cdot\left(1-\frac{1}{T_R}\right)\right\}\cdot\exp\left(\frac{V_{BE}(T)}{V_T} - \frac{V_{BE}(T_{NOM})}{V_{T_{NOM}}}\right)\cdot\exp\left(-\frac{V_{BE}(T) - V_{BE}(T_{NOM})}{V_{AR}}\right)$

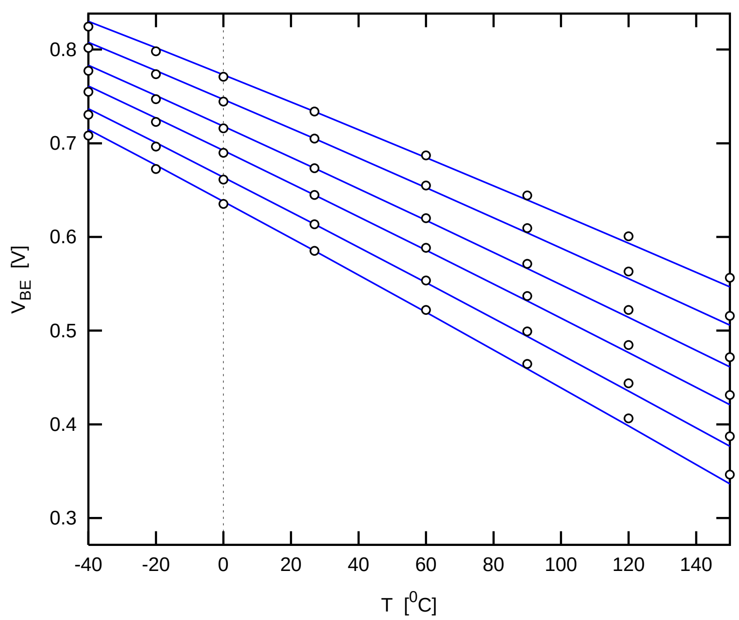
If V_{BE} is measured at different temperatures, keeping I_C constant, we can derive the following formulation and determine directly V_{GB} using a simple linear regression:

$$V_{BE}(T_{NOM})\cdot T_R\cdot\frac{V_{AR} - V_{T_{NOM}}}{V_{AR} - V_T} - V_{BE}(T) - 3\cdot\frac{V_{AR}\cdot V_T}{V_{AR} - V_T}\cdot\ln T_R = \frac{V_{AR}}{V_{AR} - V_T}\cdot V_{GB}\cdot\frac{\Delta T}{T_{NOM}}$$

→ Other method usually used to extract V_{GB} [1]

Extracted data	$I_S(T)$ data
Required model parameters	$C_{10}(T)$, $Q_{P0}(T)$
Procedure	Linear regression on the curve: $\ln\left(\frac{C_{10}(T)}{Q_{P0}(T)} \cdot \frac{Q_{P0}(T_{NOM})}{C_{10}(T_{NOM})} \cdot \left(\frac{T_{NOM}}{T}\right)^3\right) = \frac{V_{GB}}{V_{T_{NOM}}} \cdot \frac{\Delta T}{T}$
Related HICUM parameter	V_{GB}





[1] M. Schröter, “Methods for extracting parameters of geometry scalable compact bipolar transistor models”, CEDIC

➔ Bandgap voltage temperature dependence parameter

The saturation current is given by:

$$I_S(T) = I_S(T_{NOM}) \cdot T_R^{\ 3} \cdot \exp\left\{\frac{V_{GB}}{V_{T_{NOM}}} \cdot \left(1 - \frac{1}{T_R}\right)\right\}$$

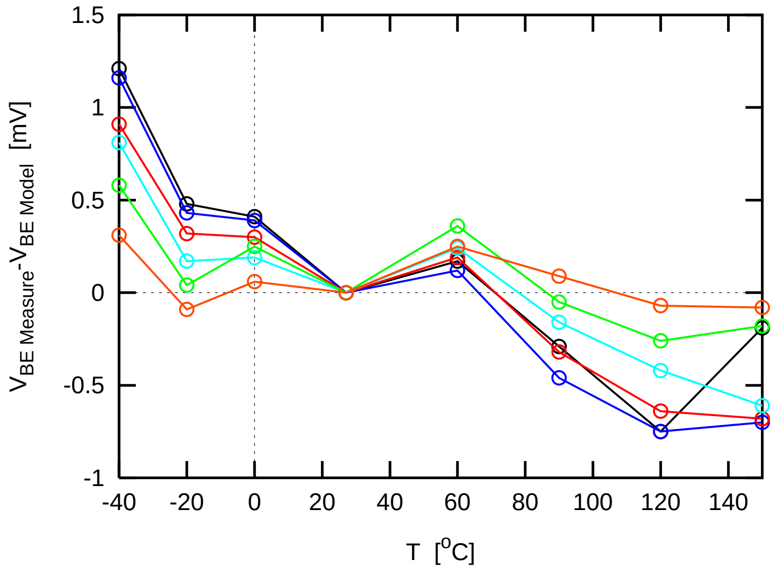
Thus, as $I_S(T) = \dfrac{C_{10}(T)}{Q_{P0}(T)}$:

$$\frac{C_{10}(T)}{Q_{P0}(T)} = \frac{C_{10}(T_{NOM})}{Q_{P0}(T_{NOM})} \cdot T_R^{\ 3} \cdot \exp\left\{\frac{V_{GB}}{V_{T_{NOM}}} \cdot \left(1 - \frac{1}{T_R}\right)\right\}$$

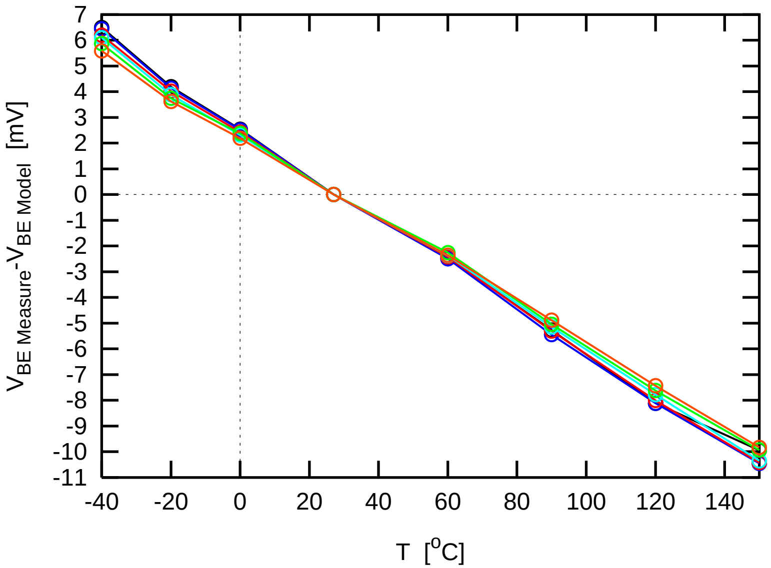
Finally, VGB is determined by a linear regression on the following formulation:

$$\ln\left(\frac{C_{10}(T)}{Q_{P0}(T)} \cdot \frac{Q_{P0}(T_{NOM})}{C_{10}(T_{NOM})} \cdot \left(\frac{T_{NOM}}{T}\right)^3\right) = \frac{V_{GB}}{V_{T_{NOM}}} \cdot \frac{\Delta T}{T}$$

Error due the direct extraction on electrical data

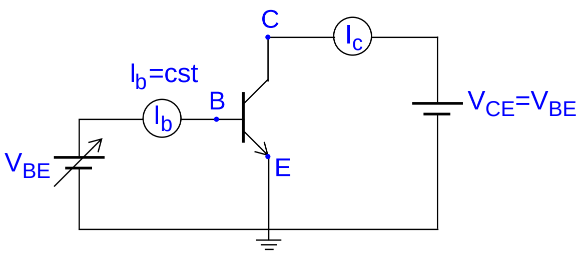


Error due the extraction on $I_S(T)$ curve



→ DIRECT EXTRACTIONS FROM TEMPERATURE MEASUREMENTS GIVE MORE PRECISE RESULTS

4.3. Relative temperature coefficient of forward current gain



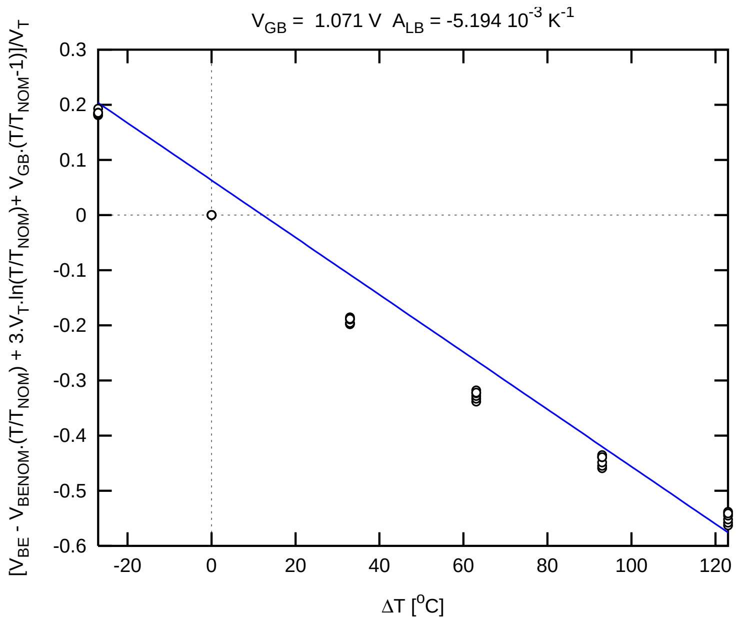
Measurement data: $V_{BE}(T)$ data at V_{BC}=0 at different constant I_B

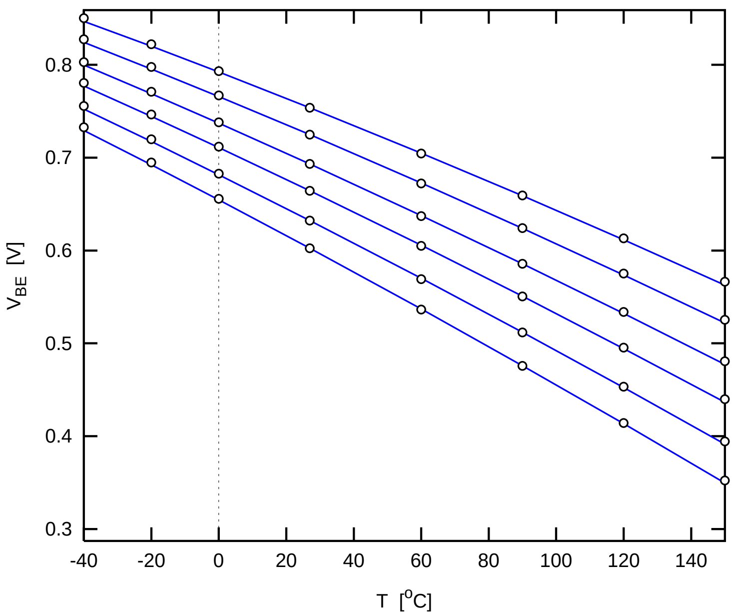
Required model parameters: V_{GB}

Procedure: Linear regression on the curve:

$$\{V_{BE}(T) - V_{BE}(T_{NOM}) \cdot T_R + 3 \cdot V_T \cdot \ln T_R + V_{GB} \cdot (T_R - 1)\} \cdot \frac{1}{V_T} = A_{LB} \cdot \Delta T$$

Related HICUM parameter: A_{LB}





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➔ Relative temperature coefficient of forward current gain

In HICUM, the temperature dependence of the forward current gain is given by:

$$B_F(T) = B_F(T_{NOM}) \cdot \{1 + A_{LB} \cdot \Delta T\}$$

Thus the temperature dependence of the saturation base current can be written:

$$I_{BS}(T) = I_{BS}(T_{NOM}) \cdot T_R{}^3 \cdot \exp\left\{\frac{V_{GB}}{V_{T_{NOM}}} \cdot \left(1 - \frac{1}{T_R}\right) - A_{LB} \cdot \Delta T\right\}$$

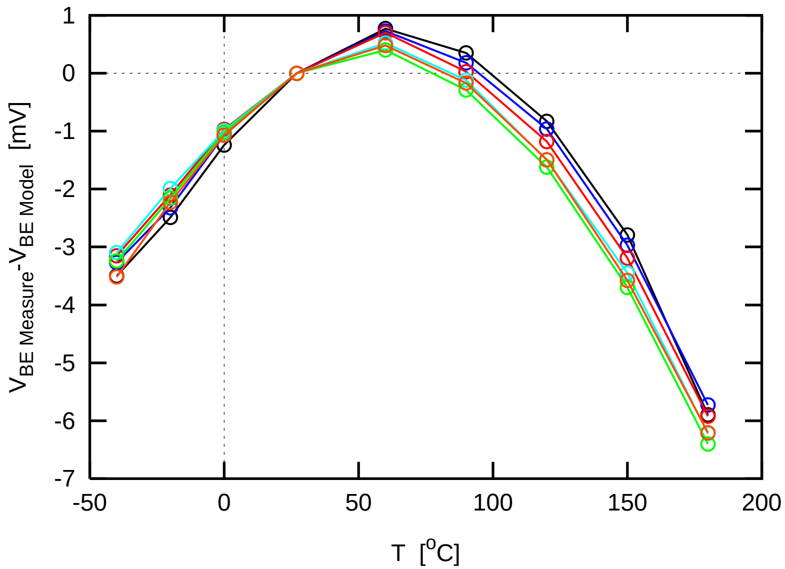
That leads finally to the temperature dependence of the “ideal“ base current I_B:

$$I_B(T) = I_B(T_{NOM}) \cdot T_R{}^3 \cdot \exp\left\{\frac{V_{GB}}{V_{T_{NOM}}} \cdot \left(1 - \frac{1}{T_R}\right) - A_{LB} \cdot \Delta T\right\} \cdot \exp\left\{\frac{V_{BE}(T)}{V_T} - \frac{V_{BE}(T_{NOM})}{V_{T_{NOM}}}\right\}$$

If V_{BE} is measured at different temperatures, keeping I_B constant, we can derive the following formulation and determine directly A_{LB} using a simple linear regression:

$$\{V_{BE}(T) - V_{BE}(T_{NOM}) \cdot T_R + 3 \cdot V_T \cdot \ln T_R + V_{GB} \cdot (T_R - 1)\} \cdot \frac{1}{V_T} = A_{LB} \cdot \Delta T$$

Error due the direct extraction on electrical data



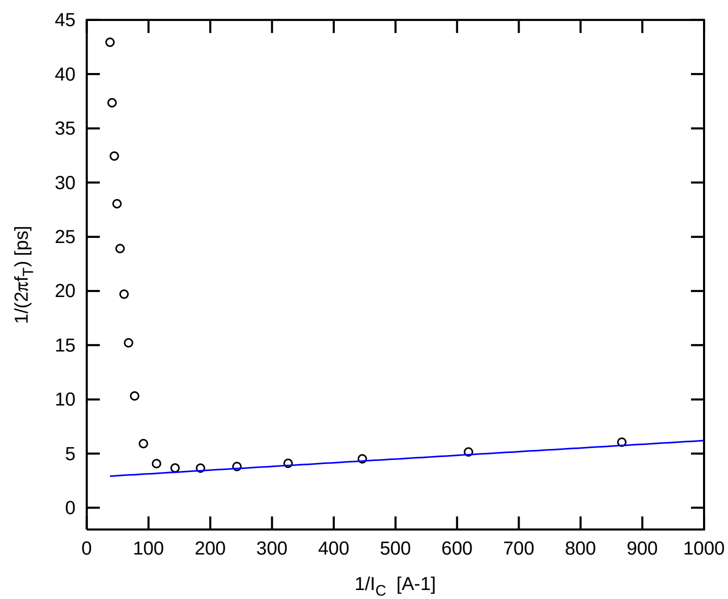
→ IMPROVEMENT IN I_B(T) MODEL DESCRIPTION

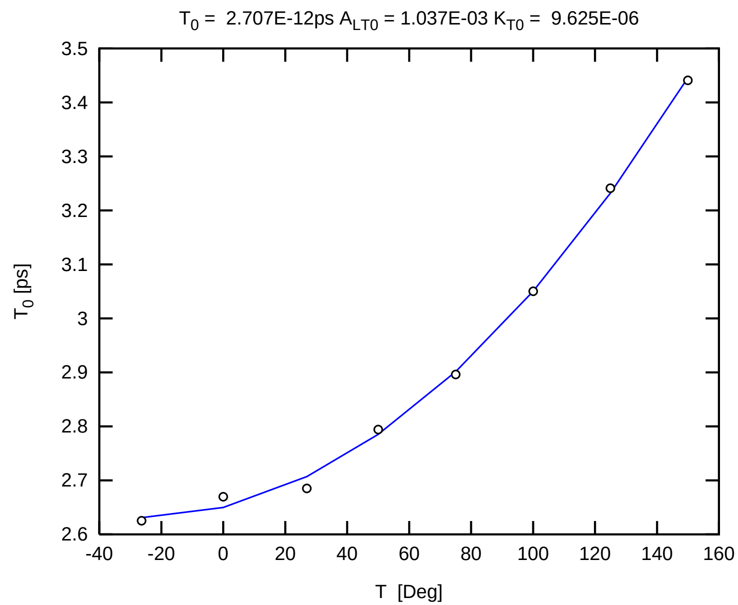
4.4. Series resistances

Measurement data	none
Required model parameters	none
Procedure	The mobility exponent can be expressed by an empirical function of the average doping concentration N of the concerned region: where x is the decimal logarithm of the doping level (1) can be directly used to calculate the temperature coefficients Z_{ETA}, knowing the average doping of the considered layer.
Related HICUM parameter	Z_{ETACI}, Z_{ETARBI}, Z_{ETARBX}, Z_{ETARCX}

4.5. Transit time at low current densities

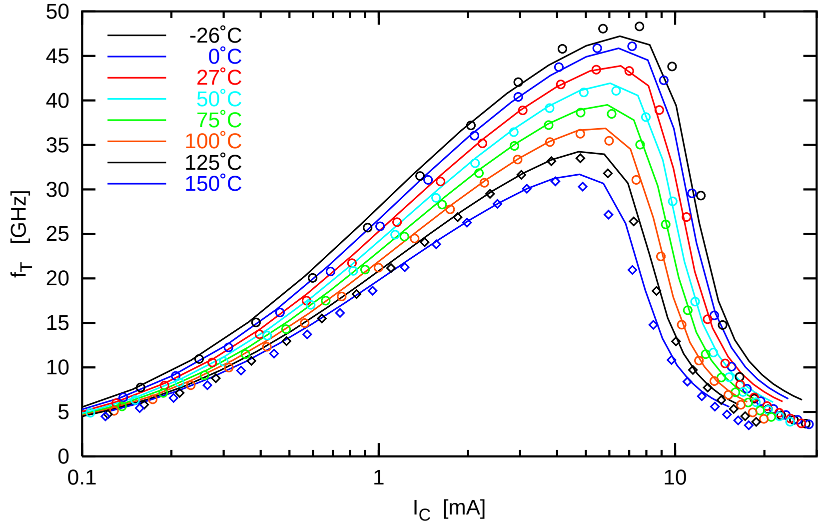
Measurement data	$\frac{1}{2\pi f_T}\left(\frac{1}{I_C}\right)$ data at V_{BC}=0 at different temperature
Required model parameters	All DC parameters, junction capacitance parameters, Z_{ETA}, V_{GB}, A_{LB}
Procedure	A temperature pre-processing gives the collector, emitter series resistances and the capacities for each temperature. The transit time T_0 is obtained from the y-intercept minus the parasitic delay $R_C(T).C_{BC}(T)$. The temperature coefficient are optimized on the characteristic $T_0(T)$
Related HICUM parameter	A_{LT0}, K_{T0}, T_0

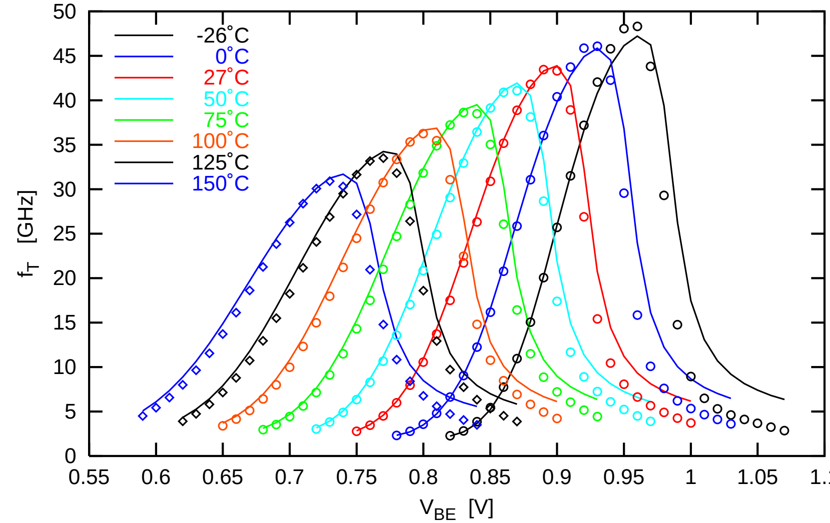




The method is tested on a transistor from a SiGe BiCMOS technology with a f_T peak at 45 GHz with one emitter contact, two base contacts, and two collector contacts.

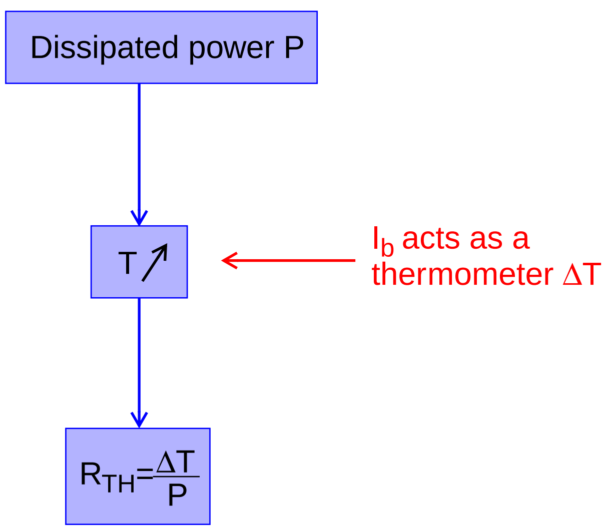
The f_T curves at V_{BC}=0 are simulated for all temperatures used for the extraction. The self-heating is not included in the following simulations.

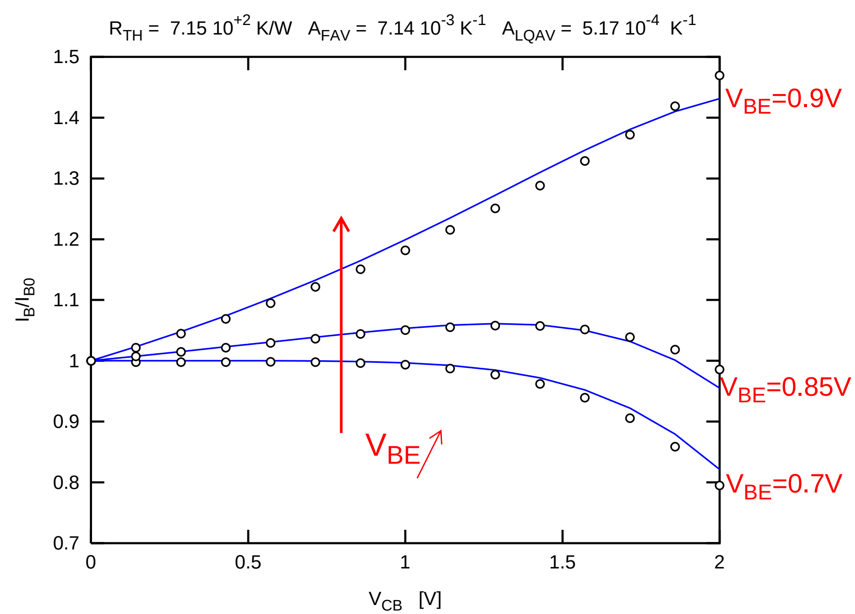




4.6. R_{TH} and BC breakdown

Measurement data	$I_B(V_{CB})$ at different V_{BE}
Required model parameters	V_{GB}, A_{LB}, Z_{ETACI}, Z_{ETARBI}, Z_{ETARBX}, Z_{ETARCX}, Z_{ETARE}, (R_{TH})
Procedure	Global optimization
Related HICUM parameter	R_{TH}, $(A_{LFAV}$, $A_{LQAV})$





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5. Summary

➔ Good description of parameter dependence with temperature at low injection

➔ Work has to be done on:

- Bandgap voltage

- Parameters describing the temperature dependence of the critical current: A_{LVS}, A_{LCES}

- Thermal coefficients of emitter resistance:

  The equation (1) is valid for mono-silicon layer. The method presented in section 4.4. can not be applied to the extraction of the temperature coefficient of the emitter poly-silicon resistance, ZETARE.
  ZETARE must be determined directly from measurements.

- Take into account the self-heating in the extraction flow.

The measurements were made on a SiGe BiCMOS technology with a f_T peak at 45 GHz with one emitter contact, two base contacts, and two collector contacts : R_{TH} = 636 $K.W^{-1}$